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PRESIDENTIAL ADDRESS

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R. Maybourn

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The Arctic has no precise boundary but it may be considered variously as those areas north of the tree-line, the regions of permafrost, or where the average temperature of the warmest month is below +10 °C, all of which describe approximately the same area. The Arctic Ocean is by no means the coldest place on Earth but it is cold enough, with January temperatures averaging in the range −30 °C to −35 °C. In summer, temperatures rise to around 0 °C.

The Ocean is very large, about 14 million km^2, which is almost two-thirds of the total area of the Arctic regions. It is deep, reaching 4500 m near the Pole, but it also has extremely large and unusually shallow continental shelves extending, for example, more than 1500 km from the mainland in the vicinity of Zemlya Frantsa-Iosifa. Ice cover at its summer minimum is about 5·2 million km^2, increasing to about 11·7 million km^2 in the winter, by which time it extends to the coasts of North America and Asia, into the channels and bays of the Arctic Islands, as far south as 50° N. at Newfoundland and into the Sea of Okhotsk.

For most of us our view of Arctic geography has been conditioned by Mercator's projection. A polar projection shows a very different world where even in the depth of winter the ice-free waters of the Atlantic and the Pacific are only 2400 nautical miles apart and North-West Europe is just 3600 miles away from the Alaskan oilfields. The known resources of the lands surrounding the Arctic Ocean are immense and much more remains to be discovered. While the population of Greenland and the northern regions of the American continent is sparse, the inhabitants of Arctic Russia are, by comparison, fairly numerous, numbering something like four million people. Current interest in the Arctic stems from its considerable potential wealth, but this was not the case in the past and to put this in perspective some comment on the history of arctic navigation may be of interest.

2. ARCTIC HISTORY. The climate of the Arctic has varied considerably and the relatively mild conditions which existed during the years AD 800–1000 aided the Viking colonization of Iceland, Greenland and Newfoundland, whence the Vikings appear from archaeological evidence to have travelled as far north as some of the Canadian Arctic islands. Contact with Europe was eventually lost, and these colonists may have become absorbed into the Eskimo population.

Interest in a North East Passage as a route to China and India prompted voyages by English and Dutch seamen in the mid 1500s. These did not succeed but they led to the establishment of profitable business with Russia. The Russians themselves, and notably Peter the Great, mounted expeditions in the area to extend their Empire but it was the Swede, Nordenskiold, who first completed the transit from west to east in 1878–9.

Efforts to find a route to the Far East also prompted attempts to find a North West Passage, the existence of which was widely believed, based on hearsay and charts showing imaginary northern lands with straits transversing in an east/west direction. Cabot reached Newfoundland in 1497 and considerable stimulus was provided during the sixteenth and sevententh centuries by the great English trading houses. Typical of the voyages undertaken were Frobisher's of 1576–8 of which the first was for the Muscovy Company and, incredibly, comprised a vessel of 25 tons, another of 20 tons and a small pinnace. Ten years later Davis penetrated to 73° N. through the strait now named after him and reported the potential of Baffin Bay for whaling.

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From that time on the history of arctic navigation is the story of such famous names as Hudson, Franklin, Ross, Parry and many others. It is an astonishing story of bravery and hardship; remarkable voyages in tiny unseaworthy vessels: feats of seamanship, surveying and navigation, interwoven fatally and much too often with an inability to recognize how to come to terms with an exceedingly hostile environment and to learn from experience.

In 1616 Bylot and Baffin penetrated through Baffin Bay to about 78° N. in a remarkable voyage which discovered Jones and Lancaster Sounds but which did not gain recognition for about 200 years, when this region was next explored and Baffin's records could be verified. Exploration was not confined to sea voyages, however, and some epic overland journeys were made. Hearne reached the mouth of the Coppermine River on the north coast of Canada in 1771 and Mackenzie arrived at the mouth of the Mackenzie River where it empties into the Arctic Ocean in 1789. Both these areas were revisited by Franklin during the period 1819–27.

Because of the immense difficulties encountered, interest in the early 1800s shifted from the North West Passage towards exploiting the huge whale population to be found between Greenland and Canada. Experience in ice navigation developed rapidly, as did knowledge of how to build and equip vessels for operating in such difficult waters. Nevertheless, as early as 1742 Parliament offered a number of prizes to encourage voyages to find the Passage. The largest, to be paid on proof that a route existed, was £20000, and Parry qualified for a £5000 prize in 1820 by crossing 110° W. longitude during his voyages through Lancaster Sound and into Viscount Melville Sound. The exploits of this era cannot be dealt with adequately in a paragraph or two and deserve to be read in detail.

Ross's expedition of 1829–33 sailed with 1000 days' provisions and spent four winters in the Arctic. It identified the position of the North Magnetic Pole and added large stretches of coastline to the charts. His ship became icebound and was abandoned, but Ross reached Baffin Bay in the ship's boats and was picked up by a whaler, having lost only three of his crew during the expedition. Then in May 1845 began Franklin's ill-fated voyage, and he was last seen in July of that year in the vicinity of Lancaster Sound. In 1848 fears for his safety grew and searches were started, which continued for eleven years until remains were found in the vicinity of King William Island. These searches added greatly to knowledge of the geography of the Arctic and one of them, by McClure during 1850–4, finally proved the existence of a North West Passage. His approach was from the Pacific and the Bering Strait and his exploit earned him the £20000 prize, although he lost his ship in the ice in the process. Ironically the evidence that the Passage existed was coupled with the realization that the ice which infested it rendered it useless as a navigable route. Inevitably interest evaporated.

In 1906 Amundsen completed a three-year voyage from east to west in a 47-ton fishing boat, to become the first man to navigate the length of the

Passage. The comparable west to east transit was by Sergeant Henry Larsen RCMP in the schooner *St. Roch*, in a two-year voyage completed in 1944; he made the return voyage the same year in a single season. In 1977 Willy de Roos navigated the Passage from east to west in the steel ketch *Williwaw*. The first deep-draughted transit was by HMCS *Labrador* in 1954, and in 1958 the US nuclear submarine *Nautilus* crossed the Arctic submerged beneath the ice.

3. ARCTIC ICE. Except for the last, all these voyages were progressed during the short summer navigation season, by using inshore channels as they melted or by exploiting open leads formed in the pack by action of wind and current. However, any understanding of the potential and limitations of navigation by modern high-powered vessels within the pack requires a detailed knowledge of arctic ice. Its composition, strength and movement are extremely complex and not yet fully understood although a great deal has been learned in recent years.

The surface of the sea begins to freeze when its temperature is lowered to about -2 °C. Ice is a poor conductor of heat and, while a layer of ice perhaps 10 cm thick can form in a single day in very cold weather, the rate of growth decreases rapidly as it thickens, and the maximum thickness which unbroken ice is likely to reach is of the order of 2 or $2\frac{1}{2}$ m. The only ice to develop in this manner is to be found in sheltered inlets and channels, or offshore in shallow water, and is likely to be 'landfast' ice, large areas of smooth ice anchored to the shore. Elsewhere wind, wave and current action modify the development of ice very considerably. The two main phenomena are rafting and ridging. Rafting is the process whereby a sheet of ice is forced over another so that its thickness is doubled. Ridging occurs when ice is under pressure and a line of fracture occurs, forcing blocks of ice on top of and beneath the ice sheet to form ridges. These can occasionally have a height from crest to keel of 50 metres or more.

When sea ice first forms its crystals are fresh water, but brine is trapped between them and new ice has a high salt content. This brine slowly leaches out and any ice which survives into a second year will be comparatively salt-free and by the third year is fresh. This is very significant as the strength and hardness of ice increase as it becomes fresher and also as it becomes colder. Multi-year ice is thus very much stronger than a similar thickness of first-year ice.

Another factor which has a marked effect on the form and strength of sea ice is weathering. When ridges are first formed the blocks of ice which comprise them reflect the thickness, age and salinity of the ice sheet from which they come. There is little cohesion between them. Those beneath the ice penetrate downwards and are a loose collection at sea temperature, having a mass about seven times that of the ridge above the water so as to maintain equilibrium. The upper surface of the ridge experiences melting in the summer season, which both rounds its contours and allows fresh melt water to trickle into the crevices where it re-freezes. In time the surface of the ridge becomes lower and smoother and it becomes welded

Fig. 1. The Canadian icel

Fig. 2. The *Manhattan* st

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Fig. 1. The Canadian icebreaker *John A. MacDonald* in weathered ice, McClure Strait

Fig. 2. The *Manhattan* stuck in an old polar floe, McClure Strait

into a solid mass of great strength. Ridged ice in this form is a major component of large floes, which can be many kilometres across and which can survive for a number of years. Figures 1 and 2 show typical humocks of old polar ice in McClure Strait; they rise some 2 m above the level of the ice sheet. The pack is not solely made up of multi-year ice, however. It is fed from new ice formed during the winter, particularly from the East Siberian Sea, and also from the numerous leads which form throughout the Arctic Ocean.

Although the area of the pack at its summer minimum is less than half that of the winter maximum it does not recede to a great distance from much of the coast of Russia or Alaska and not at all from the coasts of the Canadian Arctic islands and North Greenland. However, the width of the inshore navigable waters varies greatly from season to season in any one area and sometimes, as off the north coast of Alaska in 1975, does not move offshore at all. The major ice movement is due to the Transpolar Drift Stream which carries mainly first- and second-year ice from the East Siberian Sea across the Pole and down the east coast of Greenland. There is a second major feature, however. This is the Beaufort Gyral which is a more or less closed clockwise drift between Alaska, Canada and the North Pole. The boundaries fluctuate somewhat, but floes can remain trapped in this gyral for many years and it contains the oldest and heaviest ice in the Arctic. The thickness of the pack has been investigated by many expeditions, from Nansen's in the *Fram* (1893–6) to the present day, including some which have crossed from one side of the Arctic Ocean to the other via the North Pole. There seems to be general agreement that as ice moves slowly in the Transpolar Drift Stream over a period of 3–4 years the major change in thickness arises from increases due to ridging rather than to length of exposure to low temperatures. Although considerable local variations occur the average thickness of level ice has consistently been found to be of the order of $2\frac{1}{2}$ m, and $3\frac{1}{2}$ m for all ice including ridges. Throughout the ocean, ice movement causes open water to occur on a significant scale and, although it freezes rapidly in winter, ice thicknesses below 30 cm have been recorded on about 5 per cent of occasions even in March.

While the topography of the upper surface is readily apparent and well known, the nature of the underwater surface has only become well understood since the voyages of the nuclear submarines began just over two decades ago. To date many thousands of kilometres of traces have been taken by upward-looking sonars, some of which have been analysed in great detail[1]. The picture revealed (Fig. 4) is fascinating and, indeed, chastening to would be arctic navigators. The encounter rate varies considerably, but ice-keels having depths in the range 10 m to 30 m below sea level have been observed at a rate of between 100 and 200 per 100 km. One analysis of deep keels (greater than 30 m in depth) showed 45 in a track of 3907 km, mostly in the range 30–34 m, but one exceeding 40 m. The deepest keel on record is believed to have extended to 47 m

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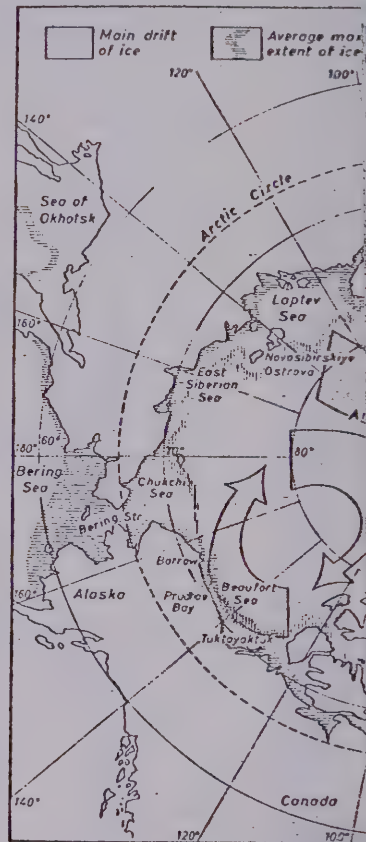

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below sea level.[2,3] The underwater profile is irregular and very variable but it cannot be accurately identified from sonar traces since it is not possible to tell at what angle a ridge has been crossed. However, it is possible to infer that the slope angle is most often around 30°, so the width of a ridge can be very considerable. Submarine voyages have confirmed the geographical distribution of ridges as being less frequent and smaller in the Transpolar Drift Stream (but increasing as progress is made towards Greenland) and numerous and deep in the Beaufort Gyral.

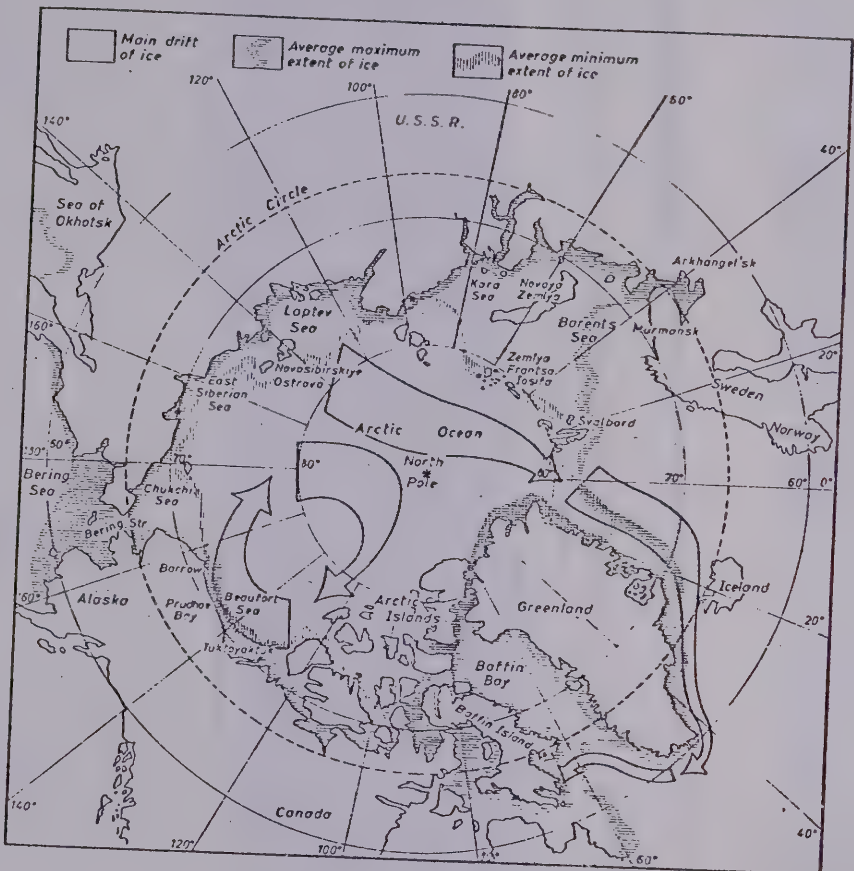

Fig. 3. The Arctic Ocean, ice conditions

The Arctic pack is of sea-water origin but a significant, if fairly local, form of ice of land origin is the iceberg; most of them originate from the glaciers of East and, particularly, West Greenland. Their appearance off the Grand Banks of Newfoundland is well known, but this is the termination of a long journey which for some can be as much as three years. Those from East Greenland travel south along the coast, round Cape

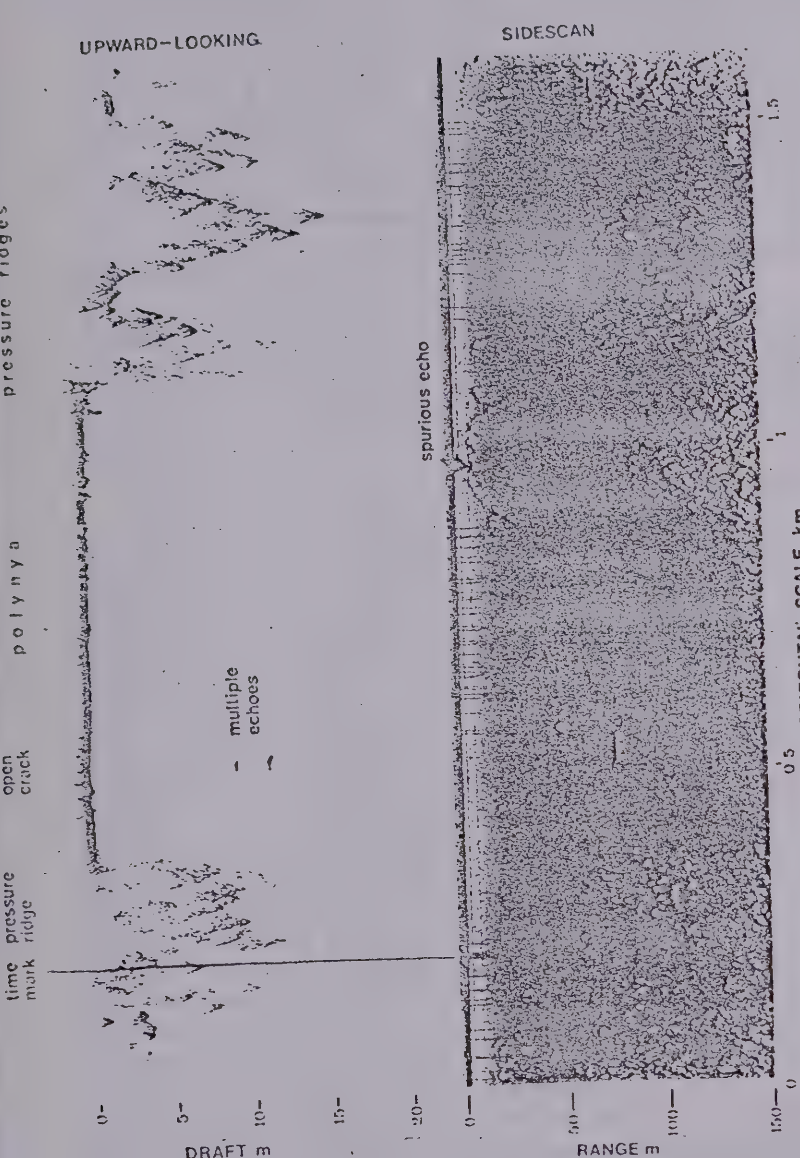

Fig. 4. Sonar traces of pack-ice (from P. Wadhams and R. T. Lowry, 4th Canadian Symposium on Remote Sensing, Quebec 1977)

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Farewell and then north again to join the bergs calved from the glaciers of West Greenland, particularly in the Disko region. They number perhaps as many as 40 000 in a year and cross Baffin Bay to travel south during the winter in the Labrador Current, to appear off Newfoundland the following summer. Some 1000 cross the 55° parallel each year and about 400 of them reach the Grand Banks.

One other form of ice is of interest. This is the ice-island which originates in the ice sheet covering the north-west coast of Ellesmere Island. Large slabs of this ice break off, in pieces sometimes 50 m or more thick. While they are not generally of very great area, a few have been large enough to accommodate arctic expeditions. They can survive in the Arctic Ocean for very many years and can cover very great distances, often circling in the Beaufort Gyral.

4. ARCTIC NAVIGATION—THE PRESENT. While a small amount of shipping has been employed for a number of years on brief summer voyages in the support of small settlements, meteorological stations and radar stations throughout the Arctic, the major reason for operating ships in the area is commercial and the major activity is to be found in Russian waters.

About two-thirds of the land within the Arctic is in the USSR, with a correspondingly high proportion of the known mineral resources. What this amounts to is interesting and helps to explain the importance of the Northern Sea Route in connecting the four northern regions of Russia. Between them they contain important iron ore reserves, they are rich in non-ferrous metals and have perhaps one-half of the very large total Soviet deposits of coal. Oil and gas are known to exist widely and it is expected that important reserves may be found on the continental shelves of the Kara and Barents Sea and of the Far Eastern Region.[4]

The American Arctic also contains important mineral wealth. Large deposits of iron ore exist on Baffin Island and non-ferrous metals have been identified on neighbouring islands. Significant finds of oil and gas have been made on the Canadian Arctic islands to the north of the North West Passage and in latitudes of 75° N. or higher. Further west, from Amundsen Gulf to the Mackenzie Delta, a great deal of drilling is taking place and important reserves of gas and oil have been discovered. The best known activity is in Alaska, where the Prudhoe Bay oilfield was discovered in 1968 and found to contain over one quarter of the proven crude oil reserves of the USA. Many other important mineral resources exist in the state; however the main interest is in oil, and exploration is extending from the mainland, northwards on the continental shelf.

Shipping activity along the Northern Sea Route is considerable and reflects fifty years or more of Russian experience in ice navigation.[5] The Soviet Union has the largest and most powerful fleet of ice-breakers in the world of which sixteen are over 10 000 s.h.p. Three of these are nuclear powered and two very powerful shallow-draughted vessels are under construction for use in the Siberian river estuaries. The number of cargo

vessels employed is large, and the 1977 Soviet merchant shipping register showed 287 ships in the top two ice-strengthened classes. These are mostly vessels in the 3000–10000 d.w.t. range but they include ten tankers of 17000 d.w.t., and a class of ten 20000 d.w.t. ore-carriers is being delivered. A recent report of considerable interest concerns nine vessels of about 15000 d.w.t. each, to be delivered by 1983. These

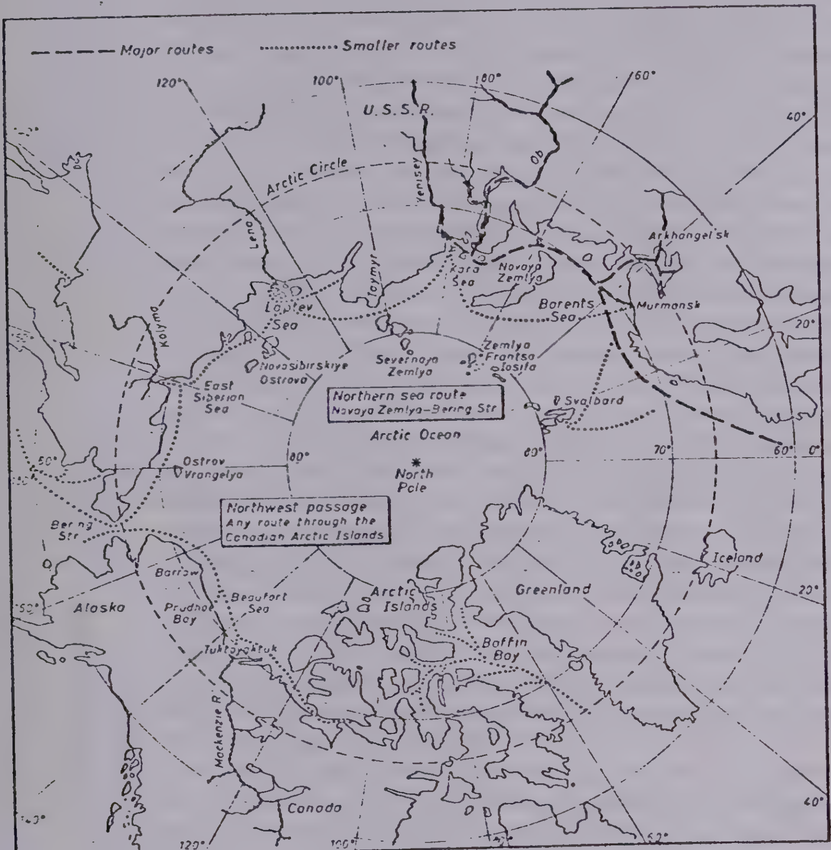

Fig. 5. The Arctic Ocean, sea routes

appear to be genuine ice-breaking cargo ships able to operate independently in ice 1 m thick. To achieve this they have 21000 s.h.p. transmitted through a controllable-pitch propeller. These sizes of vessel reflect the relatively shallow water found along the coastal routes and in the major river estuaries.

Details of the operations undertaken are sparse, but a general picture is possible, enough at any rate to indicate the nature and scope of what is

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being done. Only a few years ago the duration of navigation along the length of the route was about ten weeks, and not more than four and a half months at the western end. Since 1970 efforts have been made to extend the navigation season at both ends and the Russians now speak of year-round operations. This should be interpreted, perhaps, as an indication of intent rather than of what is being achieved, but it seems clear that the season, over some parts of the route at least, is now quite long.

There is little through traffic over the length of the route nor, probably, is there any need for it. The eastern end, to the Kolyma River (about 160° E.), is serviced from Vladivostok and the western end, to the Yenisey, from Murmansk and Arkhangel'sk. The middle section is serviced from either end but mainly from the west. Information available for 1978 is of considerable interest. Operations in the Kara Sea started in February and illustrated how important it is to utilize the severe environmental conditions to advantage where possible. By early April ten ships had landed 72 000 tonnes of cargo on to the ice, for carriage along a road over fast-ice to the shore, in an area inaccessible in the open season because of shoal water. This type of operation is carried out in many locations.

Shipping was able to enter the Yenisey during June, nearly five months after the close of the previous season. Because of severe ice in the Kara Sea, convoys were routed to the north of Novaya Zemlya as late as September, but the route appears to have been kept open at least until February 1979. It seems likely that cargo handled between Murmansk and the Yenisey could amount to around three million tonnes a year, with exports including a million tonnes of ore and 600 000 tonnes of timber.

Traffic along the central section in 1978 was hampered by difficult ice in the channel between Taymyr and Severnya Zemlya and two of the nuclear ice-breakers were working there in August. No information on cargoes carried is available. Around 400 000 tonnes of cargo were carried along the eastern sector in a relatively short season, the mouth of the Kolyma opening in mid July and the last convoy sailing from Anadyr' on the Bering Sea in late November.

Many of these voyages were by ships in convoys operating with ice-breakers. While every opportunity is taken to exploit open water in the summer season it is clear that parts of the Northern Route are often impeded by difficult ice conditions. Beyond the summer season the extent and difficulty of the ice-cover increases rapidly and success depends on adequate ice-breaker assistance, ice-strengthened vessels and considerable experience of ice navigation. An insight into what is possible may be gained from a voyage reported late in 1978. The nuclear ice breaker *Arktika* (23 400 tonnes displacement and 75 000 s.h.p.), escorting a vessel called *Lena*, left Murmansk on 22 December, in darkness and with winter well advanced, for Ostrov Greem-Bell in Zemlya Frantsa-Iosifa. The archipelago, which is in 81° N. latitude, was reached on 6 January and the operation was concluded by 3 February. *Arktika* returned to the White Sea to help keep Arkhangel'sk open throughout the winter.

The situation off the North American continent is very different, as there is no comparable pattern of trade and the shipping activity which is required is confined to the summer navigation season. This activity is by no means insignificant, however, and both Canada and the US have a number of ice-breakers, some of which are modern high-powered vessels. Until about 1970 Canadian interest in commercial shipping was mainly concentrated in the St Lawrence and in Hudson Bay but since then, perhaps stimulated by the *Manhattan* voyages of 1969 and 1970, there has been a recognition that the mineral and hydrocarbon resources of the far north are capable of being exploited if shipping suitable for operation over a substantial part of the year can be developed.

The major shipping activity in the north is in support of oil exploration and development activities. After oil had been discovered on the coast between the Mackenzie Delta and the Tuktoyuktuk Peninsula exploration began, and continued offshore in the Beaufort Sea with some success although confined to the summer season. Further to the West in Alaska, the giant Prudhoe Bay oil-field development posed logistics problems which depended on sea transportation for their solution. The coastal waters along the whole of the coast from Point Barrow to Amundsen Gulf are very shallow and the one deep harbour, at Herschel Island, has only 11 m water-depth. Cargo is moved in barges drawing not more than about 4 m, and some much less. There are two routes, one originating in central Canada and using the Hay River and Mackenzie River system, a journey of about 3000 km even before the Arctic Ocean is reached. This is a once-a-year voyage which can only begin as the summer thaw develops and is a remarkable feat of navigation through uninhabited, difficult country along a river in flood and beset with shallows and numerous hazards.

The second route is very different but equally remarkable.[6] The 'Sealift' to Prudhoe Bay is also a once-a-year operation which starts in Seattle early in June, when a large convoy leaves, to arrive at the edge of the ice off Icy Cape (to the south-west of Barrow) late in July. It then proceeds north around Point Barrow and on to Prudhoe as the ice recedes. The barges are all 'flat tops' and many are 120 m long by 30 m beam, with a cargo capacity of over 10 000 tonnes. The first major convoy was in 1970 and comprised 70 vessels in all, carrying 187 000 tonnes of cargo. Navigation is normally possible around Point Barrow early in August and the empty barges expect to return south by early September so as not to be frozen in.

Ice conditions, however, are both variable and unpredictable and this can raise serious problems, especially as such barges have no ice-breaking capability whatsoever. This was the case in 1975 when the pack failed to recede from Point Barrow and remained close inshore along the north Alaskan coast. The convoy that year comprised 47 barges and tugs and 160 000 tonnes of cargo worth $1200 million. Crucial items were 180 massive modules comprising living quarters, oil-flow stations, gas-

separation plant, a power station and other vital equipment. These were all unit loads, the heaviest of which weighed 1250 tonnes, and many weighed over 700 tonnes each. Two were as tall as a seven-storey building.

After a normal voyage north Icy Cape was reached on 23 July, but a month later progress was still not possible and heavy storms drove four barges ashore; they were only saved with great difficulty. On 2 September a narrow navigable channel opened off Point Barrow and ten barges and seven tugs passed through before the ice again closed in. The possibility of a successful transit for the remainder was seriously in doubt. The pack persisted at Point Barrow, frequently moving and under great pressure, and contained a high proportion of old polar floes. A decision was taken to return south all barges which could be unloaded in southern Alaskan ports, leaving only the large 9000 s.h.p. tugs and 15 barges, all of which were loaded with the large modules. These were now without insurance cover and valued at over $450 million. By late September new ice was forming fast on open water but on 27 September a narrow channel, about 20 km long and 1·5 km wide at its entrance, opened up inshore to Point Barrow where the edge of the pack was grounded in shallow water. At its narrowest point the obstruction was about 360 m wide and up to 10 m thick. Three USCG ice-breakers which were in attendance managed to break a narrow channel which allowed the barge convoy to pass Point Barrow, with Prudhoe Bay still 270 km to the east. Due to gales it subsequently became trapped inshore in pressure ice and it was six days before all the barges arrived. Because of the lateness of the season they were frozen in and some of the heavy modules could only be brought ashore four months later when the sea had frozen down to the sea bed.

5. THE FUTURE. *Ship Design.* It is probably fair to conclude that the development of Arctic navigation beyond what we see at the present time will depend upon significant design improvements and an increase in size and power of the vessels employed. The very high cost of such vessels can only be justified if they can be employed during a much longer season, ideally all the year round. The voyages of the *Manhattan* in 1969 and 1970 provided data from which some intelligent conclusions may be drawn regarding the likely form these vessels might take, and they also provided the basis for believing that they could be operated successfully.[7]

The strength of the hull presents no special problems, and the structure necessary to resist both the pressure of the pack and the impact of the ice is well within the design capabilities of naval architects. The optimum hull form is a more difficult matter, and an important part of *Manhattan's* research programme related to the strength of ice, and the manner in which it fractures, so that the most efficient bow and hull shape could be determined. This is not just a matter of breaking ice. The pieces can be many metres thick and, if they are not to impede the ship's progress by jamming either side of the bow, they must be displaced by the breaking action of the bow so that they are projected sideways and downwards beneath the

pack or pass beneath the hull. Much of this ice, some of it in pieces weighing many tonnes, will re-surface astern, having come up through the propellers and rudders. The after hull form, the protection provided for the propellers and rudders and their ability to absorb major and repeated impacts are matters for special attention.

While ice pressure is not a major problem so far as hull strength is concerned it is a major factor influencing the power required for propulsion. Not only does pressure make the ice-breaking process more difficult, it markedly increases friction along the length of the hull. Techniques such as bubbling air beneath the ice at the bow, or pumping ballast to induce rolling, can help to reduce the friction due to pressure.

Determining the power necessary to achieve adequate performance is, perhaps, the most difficult issue of all. Resistance due to ice varies with thickness, pressure, temperature, salinity, snow cover and the extent to which ridging and old polar floes have to be penetrated, since they cannot be totally avoided. In the summer season ice-breaking is a matter of last resort and exploiting leads or loose ice not under pressure is to be preferred. Modern ice-breakers typically have a horsepower/displacement ratio of up to 3:1, but because of their relatively small size they can be brought to a halt in moderately heavy ice. Progress then depends upon repeated ramming, often with the bow climbing up on the ice and breaking it by a downward action.

While the mode of ice-breaking with much larger vessels is essentially similar, their mass is such that fracture occurs without much vertical movement at the bow. It is of particular significance that for large-displacement vessels their momentum is such that the horsepower/displacement ratio for comparable performance drops considerably. The *Manhattan*, for example, had 42 000 s.h.p. and a displacement of about 140 000 tonnes, giving a ratio of 0·3:1 with which she achieved a very impressive capability in quite severe conditions. She did not, however, have the ability to operate successfully much beyond the summer navigation season, or to penetrate far into the permanent ice-cover of the Arctic Ocean.

To achieve a significant operational capability in any but the most difficult areas, such as the Beaufort Gyral, might well require 150 000 s.h.p. and 300 000 tonnes displacement. This of itself limits this type of operation to very large bulk-carriers. The power demand is likely to be very variable, depending on the conditions which, even in the depth of winter, could range from open water or thin new ice to heavy ridging; this would require multiple screws and the ability to provide a rapid and substantial boost to the base demand as necessary. An ability to provide a high percentage of power in reverse thrust is also essential, so as to be able to come astern if brought to a halt in heavy ice. This suggests that gas turbines might be attractive for augmenting the base load. Alternatively the total power requirement could be such as to make nuclear propulsion a contender.

Examples of the former approach are the USCG icebreakers *Polar Star* and *Polar Sea* which have diesel-electric propulsion of 18 000 s.h.p. plus gas turbines of 60 000 s.h.p.[8,9] This is very high power indeed for a displacement of 12 000 tonnes and it is transmitted through controllable-pitch propellers to achieve a continuous speed of 3 knots through ice 2 m thick.

Apart from adequate hull strength, an arctic vessel will require a number of special features to enable it to operate safely, and Canada, for example, has enacted legislation which sets structural standards, largely with a view to minimizing the risk of environmental pollution should the hull be ruptured. This is especially important in the Arctic because the very low temperatures inhibit the processes of degradation which occur elsewhere at sea; the adverse consequences arising from an oil spill could be both serious and of very long duration.

One other issue of importance is manoeuvrability, particularly in the sense of being able to turn or to steer chosen courses when penetrating heavy ice under pressure. There will always be a tendency to follow paths of least resistance. Impact with the edge of a large floe on one bow, for example, might cause a considerable change of heading very rapidly; which may indeed sometimes be beneficial, so far as forward progress is concerned. Since the path broken in the ice at the bow will not be much wider than the ship's beam, and will quickly close if under pressure, the scope for executing a turn will be severely limited and the turning circle could be very large. The *Manhattan* was designed with a shoulder forward which increased the width of the path broken in the ice and improved her ability to respond to the helm.

Ice Reconnaissance. While our knowledge of arctic ice has improved immensely, an extension of arctic navigation would benefit from better means of observing and forecasting ice conditions. Aerial reconnaissance is widely employed, both long-range and with shipborne helicopters for observing local conditions. Visual and photographic methods have considerable limitations, however. They can only be employed when visibility is adequate, and results are not always easy to interpret. A great deal of research is being carried out to develop sensors capable of measuring the surface profile of the ice, its temperature, its movement and its distribution. These include side-looking airborne radar and lasers, and satellite-mounted cameras and scanning-radiometers. The height at which satellites orbit makes resolution adequate to distinguish individual ice floes difficult to achieve, but they are capable of providing considerable quantities of more general information at frequent intervals. The high positional accuracy which Navstar will provide in due course should permit aircraft to carry out very precise ice surveys in areas required by shipping and this may prove to be an economic means of employing an expensive resource, particularly if sensors which are not dependent on visual light are employed.

Submarines. In view of the numerous under-ice voyages by submarines,

some consideration is necessary as to whether they can have a role in arctic navigation of a non-military nature. They are the only marine vehicles to which ice is no impediment so long as water depths are adequate for them to pass safely beneath. At the end of the 1960s serious consideration was given to designing a very large submarine tanker and there is no reason to doubt this is technically feasible. Being a liquid, oil can be accommodated in cargo compartments outside the pressure hull, which simplifies design. Even so the cost would have been very high and other problems, such as the acceptability of nuclear propulsion and the lack of deep water off the Alaskan coast, caused the idea to be dropped.

Routes. It seems probable that two distinct types of route are possible. The first is the deep-water route which favours the development of the large powerful vessel capable of independent operation. The second is the shallow-water route requiring smaller, less powerful vessels operating in convoy and with ice-breaker assistance. Only the latter type of operation exists at the present time, but on both the Russian and the Canadian sides of the ocean consideration is being given to the employment of larger vessels.

A major constraint for the Russians is the depth of water available, both along the northern sea route (particularly if advantage is to be taken of the open water passages which develop in coastal waters in summer) and in the entrances to the major rivers. Reports suggest that a novel alternative is being considered in the form of a vessel designed to carry eighty lighters of 450 tonnes capacity. This would be a moderately large vessel, of perhaps 40000 tonnes cargo capacity, which could operate in deeper water until the destination was reached. The barges would then be launched and taken into port by ice-breakers.

The shallow water which exists off the Arctic coast of Alaska poses even more serious problems, and the lack of harbours of even moderate depth was one of the main reasons for adopting a pipeline to the Pacific, rather than an arctic tanker route to the Atlantic, for the export of crude oil from Prudhoe Bay. Proposals to construct offshore terminals were developed but they would have been twenty miles of more from land to achieve an adequate depth of water for large tankers, and surrounded by heavy pack-ice for most of the year. Furthermore, the submarine pipelines necessary to supply such a terminal are vulnerable to damage by grounded ice, as can be seen from the numerous and often deep trenches scoured by ice in the sea bed.

The situation is different so far as north-eastern Canada and the Arctic islands are concerned. Deep water exists in Baffin Bay and major channels such as Lancaster Sound, and ship designs are being developed for the export of natural gas and iron ore. These vessels will be required to operate in an ice environment somewhat less severe than that of the Arctic Ocean, as it comprises a high proportion of one-year ice in winter and is less subject to very heavy ridging. Recent reports indicate that proposals to build some very large ice-breaking natural gas carriers are

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well advanced. They are to be 335 m long with 150000 s.h.p. gas turbines and will have a cargo capacity of 140000 m^3. When completed in 1985 they will operate the year round, from Melville Island to the east coast of Canada. If they are successful they will give a clear indication of what is necessary to achieve a genuine arctic capability – to navigate, for example, from open water at Spitzbergen via the Russian side of the Pole and on to the Bering Strait.

It may reasonably be asked why such a voyage should be attractive, as it seems unlikely that the greatly reduced length of the near great-circle route from Europe to the Pacific could offset the very high cost of an ice-breaking cargo ship. It is worth noting in this context, however, what has been achieved by the Russians in recent years. In 1977 the nuclear ice breaker *Arktika* made a successful voyage to the North Pole, leaving Murmansk on 9 August and returning on 23 August, having covered 3852 nautical miles in 14 days at an average speed of 11·5 knots. How much of this was through ice is not clear as the initial leg of the voyage was from Murmansk to the Laptev Sea, but the *Polar Record* made the following comment:

> The ice encountered, though very heavy in places and reducing speed to two or three knots, gave less trouble than had been expected, and only seven and a half days, rather than the expected 15, were spent in ice. A striking difference was noted between the ship's ability to break ice, of whatever age and thickness, in summer and its ability to break it in the winter. Extensive air reconnaissance was available, and a team of ice forecasters was on board.

Following this voyage it was announced that a cargo ship and an icebreaker would make a high-latitude voyage the following summer. The icebreaker on this occasion was *Arktika*'s sister ship *Sibir*, and they left Murmansk on 25 May 1978, at which time of year ice conditions would still be severe. The ostensible reason for the voyage was to demonstrate that year-round navigation along the Siberian coast with icebreaker escort was possible, and to examine the feasibility of the direct route across the Arctic Ocean, which is about 1300 km shorter than the coastal route from Murmansk to the Bering Strait. They passed north of the Novaya Zemlya and Novosibirskiye Ostrova, then south of Ostrov Vrangelya, to reach open water in the Chukchi Sea on 13 June: the cargo ship continued her voyage alone through the Bering Sea. The *Sibir* returned to the Barents Sea where she arrived on 5 July, having serviced a drifting ice station en route.

Whatever the real purpose of these voyages, they demonstrate a considerable ability to force ice, and support the view that a major extension of arctic navigation is not only possible but likely. The resources of the Arctic are such that it is only a matter of time before we see cargoes being moved on a scale which seemed incapable of achievement a decade ago.

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